MiTi® Developments

Mohawk Innovative Technology, Inc.

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Low-Friction, Wear-Resistant Korolon™ Coatings for High-Temperature, High-Speed, Air Foil Bearings

Mohawk Innovative Technology, Inc. (MiTi®), in a company-funded effort, has developed a series of low-friction, wear-resistant coatings for high-temperature, high-speed air foil bearings. In addition, Korolon™ 1350 has excellent thermal barrier properties (less than 2 w/m°K) and electrical resistivity (4E+12 ohm/m). A combination of these coatings and the unique design of the MiTi® air foil bearings has enabled successful operation of the foil bearings up to 810 °C (1500 °F) in bench tests. The test results have confirmed the excellent tribological behavior of Korolon™ coatings for high-speed, high-temperature, foil bearing applications. While the tribological behavior of Korolon™ coatings was determined to be a function of temperature, in most cases a maximum coefficient of friction well below 0.1 was observed during startup/shutdown periods. Subsequently, a foil journal bearing was designed and a composite Korolon™ coating applied to the bearing top foil; a dense chrome coating was applied to the journal surface. The foil bearing was installed in a turbojet engine and operated successfully to 54,000 rpm for over 70 start-stop cycles. In another application, the MiTi® journal and thrust foil bearings with Korolon™ coatings have been used in turboexpanders on US Navy aircraft carriers for seven years, accumulating over 25,000 start-stop cycles over the 28,000 hour duty cycle. The bearings were retrieved during a scheduled maintenance check-up and were found to be in excellent condition, without any damage to the coatings.

Foil bearings are particularly attractive for systems where conventional oil-lubricated or rolling element bearings are unsuitable due to temperature, speed, working fluid or any combinations thereof. Since foil bearings are oil free and can operate with ambient air, they are also an environmentally friendly solution for systems where lubricant contamination would be problematic. Applications now possible for foil bearings include aircraft gas turbine engines, auxiliary power units, microturbines, pumps, compressors, cryogenic turboexpanders and turbochargers, to name a few. Recent advances in foil bearing design have resulted in significant improvements in load capacity, damping, stiffness and high-temperature performance.

Although there is no sliding contact in the steady state operation of the foil bearing, contact between the foil and journal surfaces will occur at startup, shutdown and occasionally during overload situation that, under high-temperature conditions, limits the life of the low friction coating and, thus, the bearing. The lack of effective high temperature solid lubricant coatings and/or alternate materials currently limits the use of foil bearings to operating temperatures below 300 ºC. Therefore, reliable, long-life, high-temperature materials and coatings are necessary to transition these advanced bearing and seal technologies from ambient temperature applications to the extreme temperature environments found in gas turbine engines.

Korolon™ Coatings

Coatings for high-temperature, high-speed foil bearings must have high adhesion strength to the substrate and possess a low coefficient of friction and high wear resistance. The coatings must also be compliant to elastically deform with the bearing and possess high thermal and electrical resistance. The Korolon™ series consists of several low-friction, wear-resistant coatings (Table 1).

Table 1. Korolon™ low friction coating

	Korolon™ 700	Korolon™ 800	Korolon™ 1350
Chemical Composition	Polymer based coating with solid lubricants	Tungsten Disulfide based with solid lubricants	Nickel - Chrome based with solid lubricants
Chemical Resistance	Inert to Alkalis	Inert to Alkalis	Inert to Alkalis
Maximum Service Temperature	700 °F	800 °F	1350 °F
Application Method	Spray Gun Process	Spray Gun Process	Spray Gun Process
Recommended Substrate	Metal	Metal	Metal
Color	Grey	Black-Grey	Black-Grey
Tribological Performance	Low Friction High Wear Resistance	Low Friction High Wear Resistance	Low Friction High Wear Resistance

While Korolon™ 700 and 800 coatings are polymer based, Korolon™ 1350 series (A and B) are Nickel-chrome based coatings. All coatings contain solid lubricants and are deposited with the air spray gun process and, subsequently, cured and/or heat-treated. The air spray gun process is simple and cost effective for coating deposition. It incorporates the use of a simple spray gun with interchangeable spray nozzle tips and uses a solution state coating mixture.

Maximum allowable temperatures in static thermal tests for the Korolon™ coatings range from 370 °C for Korolon™ 700, 385 °C for Korolon™ 800 and 800 °C for Korolon™ 1350. Adhesion testing of the coatings using standard methods of bend testing, pull testing and indentation testing have all confirmed excellent bonding with nickel alloys, Figure 1 and Figure 2.

Figure 1. MiTi® Korolon™ 1350A coating adhesion bend test without delamination.

Figure 2. MiTi® Korolon™ 1350B coating adhesion bend test without delamination.

Journal Bearing Tests

Tribological tests were performed to evaluate the performance of Korolon™ coatings under simulated foil bearing applications. In one series of tests, the MiTi® journal bearing tribometer was used with a partial arc journal bearing having a diameter of 38.1 mm. The foil bearing consisted of a bump foil and a top smooth foil. The top surface of the top foil was coated with the Korolon™ coatings for evaluation. The journal was made from Inconel 718 and coated with thin chromium plating (using the Electrolizing™ process). The top foil was made from Inconel X-750. The following test conditions were used:

- Maximum speed: 20,000 rpm
- Pad temperature at start: room temperature
- Number of cycles: 500
- Cycle duration: ~ 30 s
- Normal load: 7-21 kPa (based bearing projected area)
- Time at full speed: ~ 4 s
- Dwell time: ~ 16 s

Each test cycle consisted of increasing the rotational speed up to 20,000 rpm and holding the speed constant at this value for approximately 4 s. The motor was then shut off, allowing coast down to a complete stop. The recorded signals included speed, friction force, pad temperature, oven temperature and ambient relative humidity and temperature.

Typical data for the Korolon™ coatings shown in Figure 3, Figure 4 and Figure 5 confirm the excellent tribological behavior of the coatings. The coefficient of friction at shutdown is about 0.1 for all three coatings and does not change with the progression of the testing. These coatings have been successfully tested up to 5,000 start-stop cycles without any damage to the coatings.

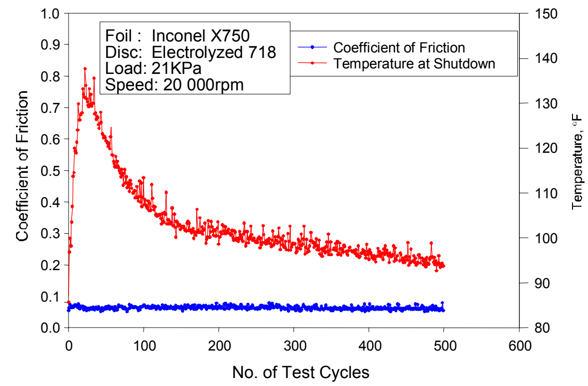

Figure 3. Shutdown coefficient of friction for Korolon™ 700 in journal bearing tests.

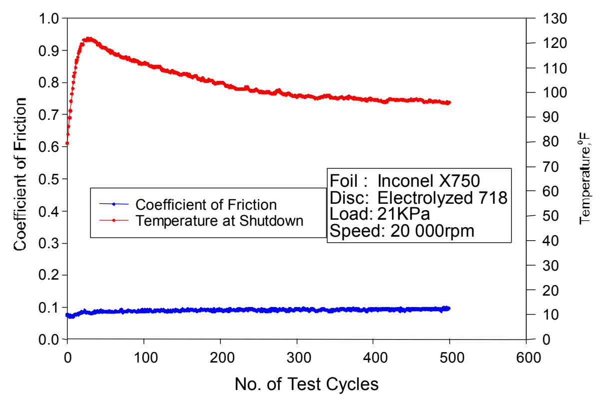

Figure 4. Shut-down coefficient of friction for Korolon™ 800 in journal bearing tests.

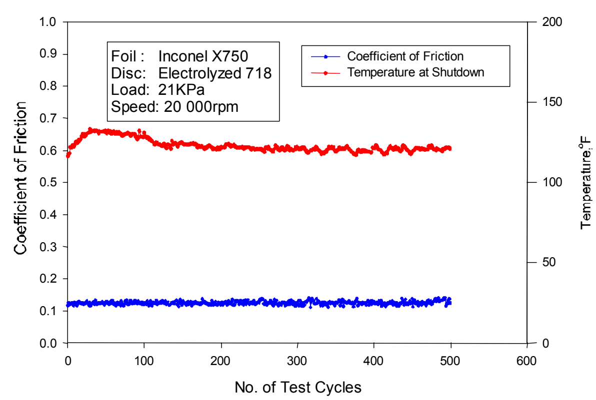

Figure 5. Shutdown coefficient of friction for KorolonTM 1350 in journal bearing tests.

Thrust Bearing Tests

In another test series, the coatings were evaluated in a simulated thrust bearing configuration to evaluate different coating combinations on the foil bearings and the counterface. Particular emphasis was given to the influence of temperature on the tribological behavior at the contacts. Several different Korolon™ coatings were used to coat the Inconel X-750 top foil, including a composite coating consisting of Korolon™ 1350A (~ 25 µm) with an overcoat of Korolon™ 800 (~ 25 µm). The counterface Inconel 718 disks were coated with PS304 (less than 120 µm), hard chrome (less than 180 µm), dense chrome (~ 5 µm) and Korolon™ 1350B (~ 5 µm).

The MiTi® high-speed, high-temperature tribometer was used to investigate wear phenomena between a 115 mm OD thrust disk and a single thrust pad mounted on a pad holder. The disk-pad assembly is enclosed in a high-temperature oven and can be exposed to temperatures of up to 900 ºC. The normal load at contact is provided by dead weight and the maximum sliding speed is 50 m/s (10,000 rpm). The spindle speed and oven temperature can be controlled from a personal computer. A gimbal joint enables measurement of frictional force with a load cell located in the room temperature section. The following test conditions were used:

- Maximum speed: 10,000 rpm
- Pad temperature: room temperature up to 810 ºC
- Number of cycles: 500
- Cycle duration: ~ 100 s
- Normal load: 9.1 N (13.8 kPa, based on total pad area)
- Time at full speed: ~ 10 s
- Dwell time: ~ 16 s

Each test cycle consisted of increasing the rotational speed up to 10,000 rpm and holding the speed constant at this value for approximately 10 s. The speed was then reduced to about 4,000 rpm (using the drive motor as a brake), followed by coast-down with no braking to a complete stop. The recorded signals included speed, friction force, pad temperature, oven temperature and ambient relative humidity and temperature.

At the start of each test cycle, the friction coefficient rises rapidly due to a brief period of contact between the pad and the disk. As the speed is increased and full hydrodynamic air film is established, the friction quickly drops to a value less than 0.01. Toward the end of the shutdown period, friction rises again due to contact formation. The maximum value of friction force during shutdown was chosen for the determination of the reported values of friction coefficient for each cycle.

The test results confirmed the excellent tribological behavior of Korolon™ coatings for high-speed, high-temperature foil bearing applications. While the tribological behavior of Korolon™ coatings was determined to be a function of temperature, in most cases a maximum coefficient of friction less than 0.1 was observed during startup/shutdown periods, Figure 6. Tests with Korolon™ 700 and 800 showed maximum friction coefficient values as low as 0.03-0.04 up to 380 ºC, Figure 7 and Figure 8. A composite coating consisting of Korolon™ 1350A with an overcoat of Korolon™ 800 exhibited a low friction up to 590 ºC (1000 ºF), Figure 9. The coated foil surfaces survived the 500 start-stop cycles with no indications of severe wear on the pads or the disks, Figure 10. Based on the measured coefficient of friction and post-test visual inspection of the mating surfaces, the hard chrome coating proved unacceptable for high temperature applications due to extensive surface cracking. The other disk coatings exhibited excellent tribological performance.

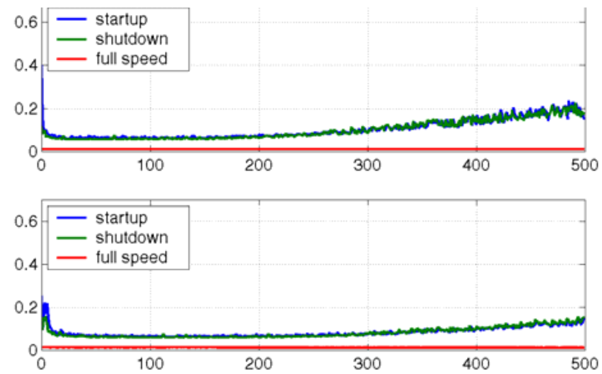

Figure 6. Typical friction values at startup, full speed, and shutdown for KorolonTM 800 for a total of 1000 test cycles.

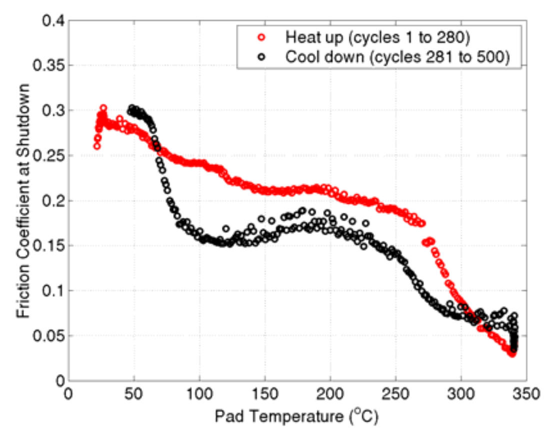

Figure 7 Friction coefficient for Korolon™ 700 coated pad against disk coated with KorolonTM 1350B for variable temperature tests.

Following these tests, a foil bearing was designed and a composite coating consisting of Korolon™ 1350A with an overcoat of Korolon™ 800 was applied to the bearing top foil; a dense chrome coating was applied to the journal surface. The foil bearing and journal were installed in a 240-pound thrust turbojet engine and operated successfully to 54,000 rpm for over 70 start-stop cycles and 14 hours. As shown in Figure 11, the tested journal and bearing suffered no damage as a result of this test, confirming the excellent tribological behavior of the Korolon™ coatings.

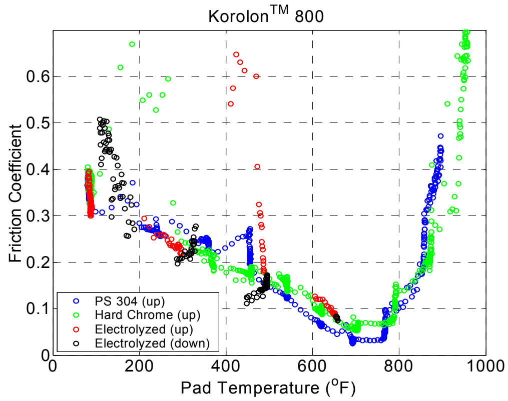

Figure 8. Friction coefficient for Korolon™ 800 pad coating against three disk coatings for variable temperature tests.

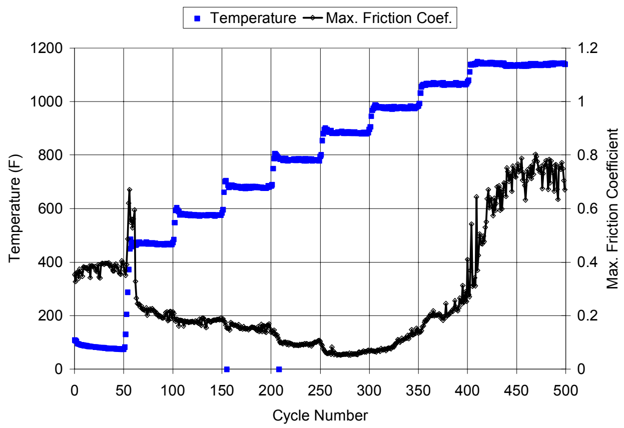

Figure 9. Temperature and friction variation during 500 cycles with composite coating of Korolon™ 1350A/overcoat of Korolon™ 800.

Figure 10. Pad with a composite coating after a high temperature test against a disk coated with hard chrome.

Figure 11. Foil bearing and journal after engine testing.

Thermal Properties

Since preliminary tests had shown that the Korolon™ coatings could exhibit thermal barrier properties, an experiment was conducted to estimate thermal conductivity of Korolon™ 1350A coating.

The insulating elements were prepared by cutting 4" OD circles out of a 0.005" thick Inconel X-750 foil and then coating both sides with about 0.005" of Korolon™ 1350A. Three such insulating elements and one uncoated Inconel X-750 foil were then sandwiched between a 0.25" thick top plate and a 0.3" thick base, which were both made of Hanes 230 high temperature alloy. While the top plate of the stack was exposed to a high temperature in the oven, the bottom base plate was water-cooled, promoting heat transfer in the top-to-bottom direction. Six type K thermocouples (TC1-TC6) positioned between the foils monitored the temperatures across the stacks. Data from this setup revealed a thermal conductivity of about 1.4 W/m K. This value compares favorably with the reported thermal conductivity of state-of-the-art ceramic thermal barrier coatings like Yttrium stabilized Zirconia (conductivity of 1.4 to 2.5 W/m K) or Mullite/BSAS-based coatings (conductivity of about 3 W/m K). More detailed information will be forthcoming in a future MiTi® Developments Newsletter.

Road Paved for Further Developments

These developments offer expanded opportunities for the application and use of compliant foil bearings in machines such as industrial compressors, microturbine generators, gas turbine engines, auxiliary power units and even large compressors for hydrogen or natural gas in pipeline applications. Korolon™ coatings may also be considered for applications requiring thermal barriers and/or electrical media requiring high-temperature wires for windings, etc.

MiTi® is a high-speed, rotating machinery research, advanced product development and manufacturing company. MiTi® designs, develops and manufactures: high-speed, oil-free, electric motors; compliant foil bearings and compliant foil seals. Company expertise and products also include rotating machinery system design; advanced high temperature, low friction coatings and specialized custom test equipment such as precision tribometers for use in high-speed, high-temperature material friction, wear and lubrication testing.

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